

(19) World Intellectual Property Organization
International Bureau



(43) International Publication Date
27 March 2003 (27.03.2003)

PCT

(10) International Publication Number
WO 03/025353 A1

(51) International Patent Classification⁷: F01L 1/30, 9/04

Thomas, A.; 142 Hagar Lane, Boxborough, MA 01719 (US).

(21) International Application Number: PCT/US02/29359

(74) Agents: ROBINSON, Kermit et al.; Daly, Crawley and Mofford, LLP, 275 Turnpike Street, Canton, MA 02021 (US).

(22) International Filing Date:

17 September 2002 (17.09.2002)

(25) Filing Language:

English

(26) Publication Language:

English

(30) Priority Data:

60/322,813 17 September 2001 (17.09.2001) US

(81) Designated States (*national*): AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, MZ, NO, NZ, OM, PH, PL, PT, RO, RU, SD, SE, SG, SI, SK, SL, TJ, TM, TN, TR, TT, TZ, UA, UG, UZ, VC, VN, YU, ZA, ZM, ZW.

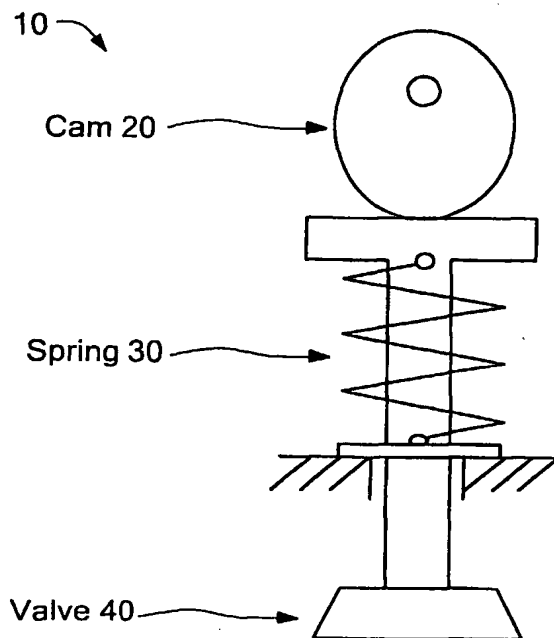
(71) Applicant: MASSACHUSETTS INSTITUTE OF TECHNOLOGY [US/US]; 77 Massachusetts Avenue, Cambridge, MA 02139 (US).

(84) Designated States (*regional*): ARIPO patent (GH, GM, KE, LS, MW, MZ, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE, SK, TR), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

(72) Inventors: CHANG, Woo, Sok; 2233 Lexington Ridge Drive, Lexington, MA 02421 (US). KASSAKIAN, John, G.; 31 Berkshire Road, Newton, MA 02460 (US). KEIM,

[Continued on next page]

(54) Title: AN ELECTROMECHANICAL VALVE DRIVE INCORPORATING A NONLINEAR MECHANICAL TRANSFORMER



(57) Abstract: The present invention provides a means to reduce holding current and driving current of EMVD's effectively and practically and to provide soft landing of a valve. The invention incorporates a nonlinear mechanical transformer as part of an EMVD system. The nonlinear mechanical transformer is designed for the spring and the inertia in the EMVD to have desirable nonlinear characteristics. With the presently disclosed invention, the holding current and driving current are reduced and soft valve landing is achieved. The nonlinear characteristics of a nonlinear mechanical transformer can be implemented in various ways. The concept of the invention can be applied not only to EMVD's but also to general reciprocating and bi-stable servomechanical systems, where smooth acceleration, soft landing, and small power consumption are desired.

WO 03/025353 A1

**Declarations under Rule 4.17:**

- as to the identity of the inventor (Rule 4.17(i)) for the following designations AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, MZ, NO, NZ, OM, PH, PL, PT, RO, RU, SD, SE, SG, SI, SK, SL, TJ, TM, TN, TR, TT, TZ, UA, UG, UZ, VC, VN, YU, ZA, ZM, ZW, ARIPO patent (GH, GM, KE, LS, MW, MZ, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE, SK, TR), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG)
- as to applicant's entitlement to apply for and be granted a patent (Rule 4.17(ii)) for the following designations AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG,

KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, MZ, NO, NZ, OM, PH, PL, PT, RO, RU, SD, SE, SG, SI, SK, SL, TJ, TM, TN, TR, TT, TZ, UA, UG, UZ, VC, VN, YU, ZA, ZM, ZW, ARIPO patent (GH, GM, KE, LS, MW, MZ, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE, SK, TR), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG)

- as to the applicant's entitlement to claim the priority of the earlier application (Rule 4.17(iii)) for all designations

Published:

- with international search report

For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

TITLE

An Electromechanical Valve Drive Incorporating A Nonlinear Mechanical Transformer

FIELD OF THE INVENTION

5 The present invention relates generally to electromechanical valve drive systems, and more specifically to an electromechanical valve drive system incorporating a nonlinear mechanical transformer.

BACKGROUND OF THE INVENTION

10 Traditional internal combustion (IC) engines are well known. In an IC engine, a camshaft (also referred to as simply a cam) acts on the valve stems of valves to open and close the valves. The timing of the valves' openings and closings is controlled by the cam design and is fixed relative to piston position since the cam is physically coupled to and driven by the crankshaft. Due to this fixed relationship between the camshaft and
15 crankshaft, the valve timing in IC engines is designed optimally at one speed and load, usually, at high speed and wide-open throttle conditions.

 Alternates to IC engines are also known. One such alternative is a variable valve actuation (VVA) system in which significant improvements in fuel efficiency, engine
20 performance, emission, and idle quality has been achieved. One of the most advanced VVA systems demonstrated to date is the BPVD (bi-positional electromechanical valve drive), which can offer cylinder deactivation, as well as duration and phase control functions, without a camshaft. Such a BPVD VVA assembly comprises a valve or valves, one or more springs, and an electromechanical actuator. In a particular BPVD,
25 two solenoids are used as the electromechanical actuator. The spring (or system of springs) is disposed such that the zero-force position for the springs is at the midpoint of the valve stroke. The acceleration curve in BPVD systems has a relatively large (theoretically infinite) time rate of change of acceleration (referred to as "jerk") at both ends of the stroke which provides a harsh landing of the valve at the end of the stroke.
30 This is one of the reasons why the idealized prior BPVD must be modified or intensively controlled to achieve a soft landing.

Even the best prior art EMVD's are very noisy due at least in part to the large jerk at both ends of the stroke. In order to reduce the large jerk associated with the prior EMVD and to reject external disturbances, active feedback control is implemented. However, in prior EMVDs with active feedback control, there are two critical problems.

5 The solenoid actuators (which are a member of the class of normal-force electromagnetic actuators, in which the force acts normal to the air gap surface) have the property that the force of a given actuator is unidirectional. Thus to provide a bi-directional force capability, two oppositely directed actuators are required. Solenoid actuators also have the property that the force coefficient (force per unit current) falls off rapidly as air gap

10 increases. As the valve approaches its intended resting place at the end of a stroke, the near actuator can easily provide a large force to draw the valve to its resting place. It is difficult not to apply too much force, contributing to a hard landing. If at any point in the transition too much force in the direction of motion has been applied, the valve will approach the end of stroke too fast, and will collide forcefully with the stop at the end of

15 the stroke. The actuator which is capable of supplying force in the direction to slow the valve near the end of stroke must act with a large air gap. That actuator will have a small force coefficient and may be unable to apply enough retarding force, even with high current. Once the valve has come to rest, the normal force actuator which holds it at rest works with a small air gap. It can therefore hold the valve at rest with a low current.

20

For ease of control, a shear force actuator is much to be preferred. These actuators are bidirectional, so the same actuator can provide force in either direction. They are commonly produced with a force coefficient which does not vary as a function of the position of the valve. This linearizes and simplifies the control problem. But

25 simple substitution of a shear force actuator for the solenoids in existing BPVD's is not the answer. The holding current to maintain the valve at both ends of the stroke is undesirably high and the concomitant power loss is high as well. Additionally, the driving current is too large to be acceptable in practice.

It would, therefore, be desirable to provide an EMVD control system having a relatively low holding current and a relatively low driving current. It would be further desirable to provide an EMVD having a relatively low holding current and a relatively low driving current while also having smooth acceleration, soft valve landing, and
5 reduced power consumption characteristics.

SUMMARY OF THE INVENTION

In accordance with the present invention, a valve drive system includes a nonlinear mechanical transformer having a motor coupled thereto. In accordance with the
10 present invention, a valve drive system includes a nonlinear mechanical transformer having a first end coupled to a portion of the system and having a second end adapted to couple to a valve. The system further includes a motor which can be electrically controlled to drive the nonlinear mechanical transformer at different speeds independently of the engine cycle. This allows the drive system to provide fully variable valve actuation
15 functions. Accordingly, the valve drive system of the present invention corresponds to an electromechanical valve drive (EMVD) variable valve actuation (VVA) system. Since the motor drives a nonlinear mechanical transformer, a valve drive system having a relatively low holding current and a relatively low drive current is provided. The present invention thus provides reduced holding current and driving current of an EMVD in an
20 effective and practical manner. The present invention achieves the reduced holding current and driving current by incorporating a nonlinear mechanical transformer as part of the EMVD system. The nonlinear mechanical transformer is designed for the spring and the inertia in the EMVD to have desirable nonlinear characteristics.

25 In one embodiment, a spring or a system of springs is disposed about the nonlinear mechanical transformer. The nonlinear mechanical transformer is designed for the spring and the inertia in the EMVD to the value with desirable characteristics. The nonlinear characteristics of a nonlinear mechanical transformer can be implemented in various ways. Additional embodiments include an inherently nonlinear spring. The
30 nonlinear spring may be in the form of a disk spring. The concept of using a nonlinear

mechanical transformer can be applied not only to EMVD's but also to general reciprocating and bi-positional servomechanical systems, where smooth acceleration, soft landing, and small power consumption are desired.

5

BRIEF DESCRIPTION OF THE DRAWINGS

The invention will be more fully understood from the following detailed description taken in conjunction with the accompanying drawings, in which:

10 Figure 1 is a diagram of a prior art valve assembly of an internal combustion engine;

 Figure 2 is a diagram of a prior art electro-mechanical valve drive;

 Figure 3 is a diagram of the free flight dynamics of a prior art electro-mechanical valve drive assembly;

15 Figure 4 is a diagram of the valve profile and its derivatives for a prior art internal combustion engine;

 Figure 5 is a diagram of the controlled dynamics of an electro-mechanical valve drive assembly including feedback control to achieve a reduced jerk profile; Figure 6 is a diagram of an electro-mechanical valve drive assembly with nonlinear transformer of the
20 present invention;

 Figure 7 is a graph showing a desired nonlinear relationship between rotational displacement of a motor and translation displacement of a valve in the present invention;

 Figure 8 is a diagram of the flight characteristics of the present invention with current injection and without current injection;

25 Figure 9 is a diagram of the current associated with the flight characteristics of Figure 8;

 Figure 10 is a diagram of the controlled dynamic characteristics of the present invention with feedback control;

 Figure 11 is a diagram of the current associated with the characteristics of Figure
30 10;

Figure 12 is a graph showing another desired relationship between rotational displacement the spring and translation displacement of a valve system incorporating a linear torsional spring and a linear, as opposed to rotary, shear force actuator;

Figure 13 is a diagram of a valve assembly utilizing a translational cam;

5 Figure 14 is a diagram of force versus stroke for a linear spring and a desired nonlinear spring;

Figure 15 is a diagram of a disk spring;

Figure 16 is a force/stroke diagram for the disk spring of Figure 15;

Figure 17a is a diagram of a front view of a valve assembly including a disk cam;

10 Figure 17b is a diagram of a side view the valve assembly of Figure 17a;

Figure 17c is a diagram of displacement versus angle for the valve assembly of Figure 17a

Figure 18a is a diagram of a front view of a valve assembly including a second embodiment of a disk cam;

15 Figure 18b is a diagram of a side view the valve assembly of Figure 18a;

Figure 19 is a diagram of displacement versus angle for an embodiment including multiple nonlinear mechanical transformers;

Figure 20A is a diagram of a modified disk cam;

20 Figure 20B is a diagram of a prototype setup including the cam of Figure 20A;

Figure 20C is a side view of the prototype set up of Figure 20B;

Figure 20D is a side view of the prototype setup showing additional components;

Figure 21A is a block diagram showing the use of a single nonlinear mechanical transformer;

25 Figure 21B is a block diagram showing an embodiment incorporating multiple nonlinear mechanical transformers to achieve partial lift control;

Figure 21C is a series of graphs showing the partial lift control achieved from the first and second nonlinear mechanical transformers;

30 Figure 22A is a block diagram of the second nonlinear mechanical transformer at a first setting;

Figure 22B is a diagram of the second nonlinear mechanical transformer at a second setting;

Figure 22C is a diagram of the second nonlinear mechanical transformer at a third setting; and

5 Figure 23 is a block diagram of the system including the first and second nonlinear mechanical transformers.

DETAILED DESCRIPTION OF THE INVENTION

A conventional valve drive for an internal combustion engine is shown in Figure
10 1. The valve drive 10 incorporates a lobed cam 20 that drives a valve 40. A spring 30 is used to bias the valve against the lobe of the cam. The cycle rate of the valve drive is directly related to speed of the engine, as typically the cam is mechanically connected to a crankshaft that drives the piston of the engine. Since the cam is mechanically connected to the crankshaft by way of a timing chain, timing belt or timing gears, the cycle time or
15 stroke of the valve is generally fixed relative to the cycle time of the engine itself.

Referring now to Figure 2, a prior art electromechanical valve drive (EMVD) 50 is shown. EMVD 50 incorporates a valve 40, a plurality of solenoids 60 and springs 70a, 70b. The EMVD of Figure 2 operates as follows. The springs 70 are provided such that
20 the springs provide approximately zero force to the valve when the valve is approximately at the midpoint between the open position and the closed position. Initially the valve is held at a non-equilibrium position at one end of the stroke by activating solenoid 60a. When the solenoid 60a is disengaged, the valve 40 travels past an equilibrium position until it reaches the other end of the stroke. The time taken by the
25 valve 40 to travel from the upper position to a lower position is known as the transition time. Solenoid 60b is engaged to maintain the valve in this position at the second end of the stroke. After a predetermined period of time, known as the holding time, the solenoid 60b is disengaged and the valve 40 returns to its original starting position.

Springs 70a, 70b play an important role in the EMVD device. The operation of the EMVD described above requires a relatively large inertial power (mass multiplied by acceleration, multiplied by velocity). This inertial power is provided by springs 70. The power consumed in an EMVD system is limited to the mechanical and electrical loss in the EMVD system and to the power required to compensate for external disturbances such as the gas force acting on the valves. In these prior art EMVDs, the spring and the inertia of the valve have linear characteristics.

Referring now to Figure 3, the free flight dynamics of the EMVD 50 of Figure 2 is shown. Curve 130 corresponds to valve position, curve 120 corresponds to valve velocity and curve 110 corresponds to valve acceleration. The valve acceleration curve 110 has periods of infinite jerk at both ends of the stroke. This is in sharp contrast to the conventional IC valve train acceleration curve 140 shown in Figure 4, which features a smooth acceleration curve. Note that the conventional IC valve train also has a smooth valve position curve 160 and a smooth valve velocity curve 150. Accordingly, due to these periods of infinite jerk in the valve acceleration 110 of the prior art EMVD valve assembly, the EMVD must be controlled to achieve a "soft" landing of the valve within the engine. In order to reduce or remove the large jerk associated with EMVD valve assemblies, active feedback control is used.

Referring now to Figure 5, the curves for a feedback controlled EMVD with a linear spring and linear inertia are shown. The curves in Figure 5 correspond to a case where a linear electric motor, or a rotary electric motor with a uniform force or torque constant over the stroke (both examples of shear force actuators) is used instead of solenoid actuators. The valve position vs. time is feedback controlled to a desired reduced jerk profile. Valve acceleration is shown by curve 170, valve velocity is shown by curve 180, valve position is shown by curve 190 and current is shown by curve 195. As shown in the curves, the jerk is reduced, due to smooth kinematic inputs. Additionally, the effect of gas force is reduced by feedback control. It is not evident from Figure 5, but the calculations which produced this figure also showed that the motor current, both during

the valve transition time and during the holding period, are unacceptably large. Figure 5 therefore shows that feedback control of a shear force actuator can eliminate the high-jerk characteristic of the prior-art EMVD, but that other features must be added to achieve acceptable motor currents.

5

Referring now to Figure 6, the present invention 200 is shown. In this embodiment the EMVD 200 incorporates a nonlinear mechanical transformer 210. A motor 260 is coupled through a member 262 to a rotary cam 230. The motor 260 turns the member 262, which in turn causes the cam 230 to rotate. Rollers 240 are free to rotate
10 about their axes 242 and roll over first and second opposing surfaces of the rotary cam 230. The turret 250 is connected to the rollers 240 and the valve 270. The mechanism comprising the rotary cam 230, the rollers 240, and the turret 250 cooperate to function as a nonlinear mechanical transformer 210. The turret 250 and the valve 270 are free to move up and down and are constrained by a linear spring 280, but are fixed rotationally.
15 With this nonlinear mechanical transformer 210, the stiffness or the inertia for vertical motion of the valve 270 or rotational motion of the motor 260 can be designed with substantial flexibility. The springs 280 are provided such that the springs provide approximately zero force to the valve when the valve is approximately at the midpoint between the open position and the closed position. With such an arrangement the
20 majority of the work involved in moving the valve is performed by the springs. This results in a concomitant reduction in the holding and driving current required by the motor.

Figure 7 shows a desirable relation between the rotational displacement of the motor and the translation displacement of the valve. With the characteristic of Figure 7,
25 both holding and driving current are reduced. The reflected force of the linear spring 280, resulting in a spring torque on the motor side, depends on the design of the nonlinear mechanical transformer 210. The mechanical holding force in the motor side can be reduced at both ends of the stroke of a valve if the slope ($dz/d\Theta$) of the mechanical transformer in Figure 7 is almost flat at both ends of the stroke of a valve. Therefore, the
30 holding current doesn't have to be large and power consumption is reduced. Also, since

the effective moving inertia, viewed from the valve side, increases at both ends of the stroke due to the nonlinear transformer characteristic, the acceleration of the EMVD incorporating the nonlinear mechanical transformer is inherently smooth and small at the ends of the stroke. Therefore, the driving current for achieving smooth acceleration can
5 be reduced passively, because the desired position-versus-time characteristic is created mechanically instead of electrically.

The use of the nonlinear mechanical transformer has the adverse effect of deteriorating the free flight transition time from one end of the stroke to the other end of
10 the stroke. This is due to the acceleration at both ends of the stroke being very low. Injection of electrical currents into the motor at both ends of the stroke is used to avoid the deterioration of the free flight transition time. In order to confirm the benefits of the current injection technique, the flight dynamics in time domain of the EMVD with the nonlinear mechanical transformer, both with current injections and without current
15 injections is shown in the curves 300, 310, 320 and 330 of Figures 8 and 9. Except during the current injection intervals shown in Figure 9, the dynamic characteristics shown in Figure 8 are undriven, or free response to a step to zero in restraining force. Also, the dynamic model relating Figures 8 and 9 does not include any friction, gas load, or damping terms. As can be seen from the graphs, the transition time is reduced when
20 the current injection technique is implemented. Figures 10 and 11 show curves 340, 350, 360 and 370 of a simulation result for a feedback controlled EMVD with a nonlinear mechanical transformer. As shown in curve 340, the jerk is small owing to the use of the nonlinear mechanical transformer. This reduced amount of jerk is achieved with small driving and holding currents (shown in curve 370) without deteriorating the free flight
25 transition time. This nonlinear mechanical transformer concept of the invention can be applied to not only normal force EMVD's as in prior art but also shear force EMVD's as in the embodiments illustrated here.

Figure 12 shows another desirable relation between the rotational displacement of
30 a motor and the translation displacement of a valve. In this design, in order for the system

to have desirable nonlinear dynamics, a linear torsional spring replaces the linear spring in Figure 6, and the torsional spring is located to the rotary side of the nonlinear mechanical transformer instead of the valve side. Additionally the rotary motor in Figure 6 is removed and replaced with a linear motor on the valve side of the nonlinear mechanical transformer. Since the reflected force of a torsional spring force in the motor side and valve side is small at both ends of the stroke due to the nonlinear transformer characteristic in Figure 12, the acceleration of the EMVD incorporating this mechanical transformer is inherently smooth and small at the ends of the stroke. This is a duality version of the system in Figure 6.

Figure 13 shows another example of a nonlinear mechanical transformer 400. In this design, a translational cam is used instead of a rotary cam. The valve features a recessed portion wherein rollers 430 are provided. The rollers 430 are held in place vertically by guides 450. The rollers are biased in a horizontal direction by linear springs 440. With this mechanism, the stiffness for vertical motion of the valve 420 can also be designed with substantial flexibility.

Referring now to Figure 14, a force stroke curve 460 for a linear spring is shown as is a force stroke curve 470 for a nonlinear spring. Instead of a nonlinear mechanical transformer, a nonlinear spring having a force stroke curve as shown in Figure 14 can directly be used for the same purpose of the reduction of holding and driving currents.

Figure 15 shows one example of a nonlinear spring 500 having an approximately appropriate spring characteristic, a so-called disk spring. Figure 15 shows a top and a side view of such a disk spring. Figure 16 is the spring force stroke curve 510 of the disk spring 500. A stack of disk springs in series or parallel can be used to obtain an appropriate spring characteristic. Simple disk spring stacks have a unidirectional force versus stroke characteristic, so two stacks are required for the desired bi-directional characteristic.

Referring now to Figure 17a-b, an embodiment 600 of a valve drive incorporating a disk cam 620 as a nonlinear mechanical transformer is shown. The motor shaft 610 is rigidly connected to the disk cam 620. The disk cam 620 has a generally circular shape and further includes a shaped slot 625. A roller 640 connected to the valve 630 rolls over
5 either top or bottom surface of the slot of the disk cam 620. The disk cam 620 is free to rotate with the motor shaft 610. The valve 630 and roller 640 are free to move up and down along a line and constrained from other motions. This design is simple and compact, but additional power loss is expected due to the reversal of the rotational direction of the roller in the middle of the stroke. However, the loss is relatively small
10 compared to gas power. A displacement/angle diagram for this embodiment is shown in Figure 17c.

Another embodiment is shown in Figures 18a-b wherein the generally circular shaped disk cam of Figure 17a is replaced with a disk cam 621 which has a flattened
15 outside portion proximate the shaped slot 625. The conjugate disk cam of Figure 18a-b can eliminate power loss described above with respect to the embodiment utilizing the generally circular disk cam 620. A displacement/angle diagram for this embodiment is the same as shown in Figure 17c.

20 The proposed EMVD can offer a partial lift control function as well. Another nonlinear mechanical transformer plus the original nonlinear transformer can achieve this assuming that the additional nonlinear mechanical transformer controls the amplitude of the nonlinear transformer modulus as shown in Figure 19.

25 Referring now to Figure 20A a disk cam incorporated in a further embodiment is shown. The disk cam 710 includes a first aperture 720 for mounting to a motor. The aperture also provides a center about which the cam rotates a predetermined portion of a revolution about the aperture. Cam 710 further includes a slot 730 in which a roller
rides.

30

Referring now to Figures 20B-D the cam is shown in a prototype test arrangement 700. Cam 710 is coupled to motor 750. Motor 750 provides left and right rotation of the disk cam, and is computer controlled. A cam follower 760 is provided with a roller 740. Roller 740 rides in slot 730 of disk cam 710. There is clearance between the roller 740 and one surface of slot 730 as the disk cam oscillates. Attached to the cam follower is a valve stem 770 and attached to valve stem 770 is valve 780. As the disk cam is cycled between clockwise and counter-clockwise rotation, roller 740 and cam follower 760 provide for generally vertical movement of valve stem 770 and valve 780. The prototype test arrangement further includes a support bearing 790 which supports the end of the motor arm on which the disk cam is attached.

For reasons of clarity, coil springs 800 and 810 are not shown in Figures 20B and 20C. The springs 800 and 810 are shown in Figure 20D. The springs are shown surrounding portions of valve stem 770.

Referring now to Figures 21A-23, an embodiment which provides for partial lift control of the valve is shown. This embodiment incorporates a second nonlinear mechanical transformer, disposed between the first nonlinear mechanical transformer and the valve to provide partial lift control of the valve. As shown in Figure 21A, and described in detail above, a motor 810 is coupled to a first nonlinear mechanical transformer 820 (e.g. a disk cam). This provides for the desired movement of the valve 830 while providing soft landing of the valve.

In order to provide the partial lift control a second nonlinear mechanical transformer 840 is attached between the first nonlinear mechanical transformer 820 and the valve 830, as shown in Figure 21B. The utilization of the second nonlinear mechanical transformer in series with the first nonlinear mechanical transformer provides for a scaling of the translation displacement associated with the rotational displacement and also for a shifting of the mid-stroke displacement associated with the scaled

translation displacement. This is shown in the diagrams of Figure 21C and in Figures 22A-C.

The second nonlinear mechanical transformer has a plurality of settings which are used to provide the partial lift control function. The action of the second transformer in the illustrated embodiment is to relate Z_1 and Z_2 by

$$Z_2 = \alpha Z_1 + \beta$$

To achieve the intended action, α and β are adjusted following a fixed relationship $\beta = \alpha Z_0 - Z_0$.

For each of the examples shown in Figure 21C and 22A-C:

at $\alpha=1$, $\beta = 0$;

at $\alpha = 1/2$, $\beta = \alpha Z_0 - Z_0 = -1/2 Z_0$;

at $\beta=1/4$, $\beta = \alpha Z_0 - Z_0 = -3/4 Z_0$; and

at $\alpha=0$, $\beta = -Z_0$.

In general, for $0 \leq \alpha \leq 1$, $Z_2 = \alpha Z_1 + (\alpha Z_0 - Z_0)$.

By way of the second mechanical transformer coupled between the first nonlinear mechanical transformer and the valve, partial lift control is provided.

Referring now to Figure 23 a preferred embodiment of the second nonlinear mechanical transformer is shown. Other embodiments which provide a similar function may also be used to provide the partial lift control functionality. In this embodiment motor 810 drives a first nonlinear mechanical transformer 820. Coupled to the first nonlinear mechanical transformer is second nonlinear mechanical transformer 840. Second nonlinear mechanical transformer, in this embodiment, comprises an arm 842 and a movable pivot element 844. A first end of the arm 842 is coupled to the output of the first nonlinear mechanical transformer. The second end of arm 842 is coupled to valve 830. The pivot element 844 is movable in both a horizontal and vertical direction. Movement of the pivot point 844 in the horizontal direction provides for scaling of the movement of the second end of arm 842, and the valve 840. Movement of the pivot point

in the vertical direction provides shifting of the movement of the second end of arm 842, and the valve 840.

5 The pivot element of the second nonlinear mechanical transformer may be moved dynamically, preferably during a rest period of the valve cycle. This provides for stroke-by-stroke partial lift control of the valve during operation of the valve and engine.

10 As discussed above the present invention incorporates a nonlinear mechanical transformer as part of an EMVD system. The nonlinear mechanical transformer is designed for the spring and the inertia in the EMVD to have desirable nonlinear characteristics. With the presently disclosed invention, the holding current and driving current are reduced. The nonlinear characteristics of a nonlinear mechanical transformer can be implemented in various ways. The invention can be extended to general servomechanical systems, in particular, systems performing reciprocating and bi-
15 positional motion where smooth acceleration, soft landing, and low power consumption are required. The nonlinear characteristics discussed in this disclosure are provided by way of example, as the invention is intended to include other nonlinear characteristics having similar benefits.

20 Having described preferred embodiments of the invention it will now become apparent to those of ordinary skill in the art that other embodiments incorporating these concepts may be used. Accordingly, it is submitted that that the invention should not be limited to the described embodiments but rather should be limited only by the spirit and scope of the appended claims. All publications and references cited herein are expressly
25 incorporated herein by reference in their entirety.

CLAIMS

What is claimed is:

1. A valve drive assembly comprising:
5 a motor;
a nonlinear mechanical transformer coupled to said motor;
a valve connected to said nonlinear mechanical transformer, wherein said valve is movable by said nonlinear mechanical transformer and said motor between a first position wherein the valve is open and a second position wherein the valve is closed; and
10 at least one spring disposed to act upon said nonlinear mechanical transformer, said at least one spring providing approximately zero pressure to said nonlinear mechanical transformer when said valve is at a position generally midway between said first position and said second position.
- 15 2. The valve drive assembly of claim 1 wherein said nonlinear mechanical transformer comprises:
a cam coupled to said motor;
a turret disposed about said cam, wherein said valve is connected to said turret;
and
20 at least one roller disposed between said cam and said turret.
3. The valve drive assembly of claim 1 further comprising at least one spring disposed between said nonlinear mechanical transformer and a frame.
- 25 4. The valve drive assembly of claim 2 wherein said cam comprises a rotary cam.
5. The valve drive assembly of claim 1 wherein current is injected into said motor at both ends of a stroke for reducing a free flight transition time of said valve.

6. The valve drive assembly of claim 1 wherein said spring comprises a linear spring.
7. A valve drive assembly comprising:
- 5 a linear motor;
- a valve connected to said linear motor wherein said valve is movable by said motor between a first position wherein the valve is open and a second position wherein the valve is closed;
- a nonlinear mechanical transformer coupled to said linear motor and said valve;
- 10 at least one torsional spring disposed to act upon said nonlinear mechanical transformer, said at least one torsional spring providing approximately zero pressure to said nonlinear mechanical transformer when said valve is at a position generally midway between said first position and said second position.
- 15 8. The valve drive assembly of claim 7 wherein current is injected into said motor at both ends of a stroke for reducing a free flight transition time of said valve.
9. A valve drive assembly comprising:
- a motor;
- 20 a valve coupled to said motor, said valve movable between a first open position and a second closed position; and
- at least one nonlinear spring disposed between said valve and a support, said nonlinear spring providing approximately zero pressure to said valve when said valve is at a position generally midway between said first position and said second position.
- 25 10. The valve drive assembly of claim 9 wherein said nonlinear spring comprises at least one nonlinear disk spring.
11. A valve drive assembly comprising:
- 30 a motor;

a nonlinear mechanical transformer coupled to said motor;

a valve connected to said nonlinear mechanical transformer, wherein said valve is movable by said motor and said nonlinear mechanical transformer between a first position wherein the valve is open and a second position wherein the valve is closed; and

5 at least one spring disposed to act upon said valve, said at least one spring providing approximately zero pressure to said valve when said valve is at a position generally midway between said first position and said second position.

12. The valve drive assembly of claim 11 wherein said nonlinear mechanical
10 transformer comprises a disk cam, said disk cam including a slot and wherein said valve includes a roller, said roller at least partially disposed within said slot.

13. The valve drive assembly of claim 12 wherein said disk cam has a generally
circular
15 shape.

14. The valve drive assembly of claim 12 wherein a first portion of said disk cam has a generally circular shape and a second portion of said disk cam has a generally flattened
shape.

20

15. The valve drive assembly of claim 12 wherein said disk cam has a first portion having a first curved surface, a second portion having a second curved surface and a transition portion connecting said first portion to said second portion.

25 16. The valve drive assembly of claim 15 wherein said second portion is larger than said first section.

17. A valve drive assembly comprising:

a motor;

30 a first nonlinear mechanical transformer coupled to said motor;

a coupler coupled to said first nonlinear mechanical transformer;

at least one spring disposed to act upon said coupler, said at least one spring providing approximately zero pressure to said coupler when said coupler is at a position generally midway between an uppermost position and a lowermost position;

5 a second nonlinear mechanical transformer coupled to said coupler

a valve connected to said second nonlinear mechanical transformer, wherein said valve is movable by said motor, said first nonlinear mechanical transformer and said second nonlinear mechanical transformer between a first position wherein the valve is open and a second position wherein the valve is closed.

10

18. The valve drive assembly of claim 17 wherein said first nonlinear mechanical transformer comprises a disk cam.

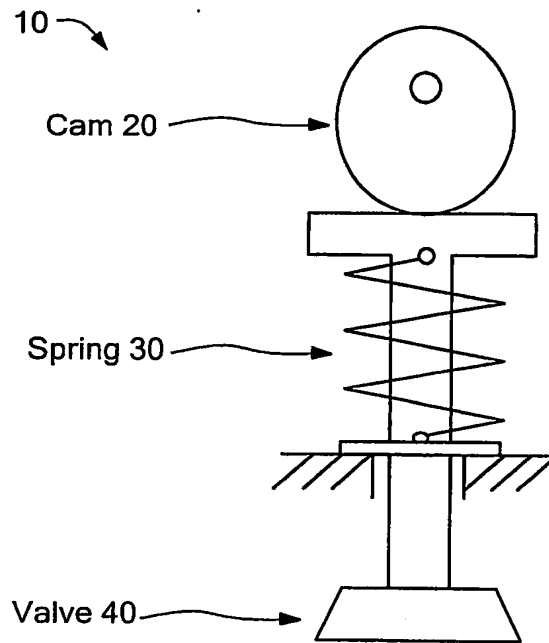
15 19. The valve drive assembly of claim 17 wherein said second nonlinear mechanical transformer comprises:

an arm; and

a pivot element coupled to said arm and wherein said arm is movable about said pivot element.

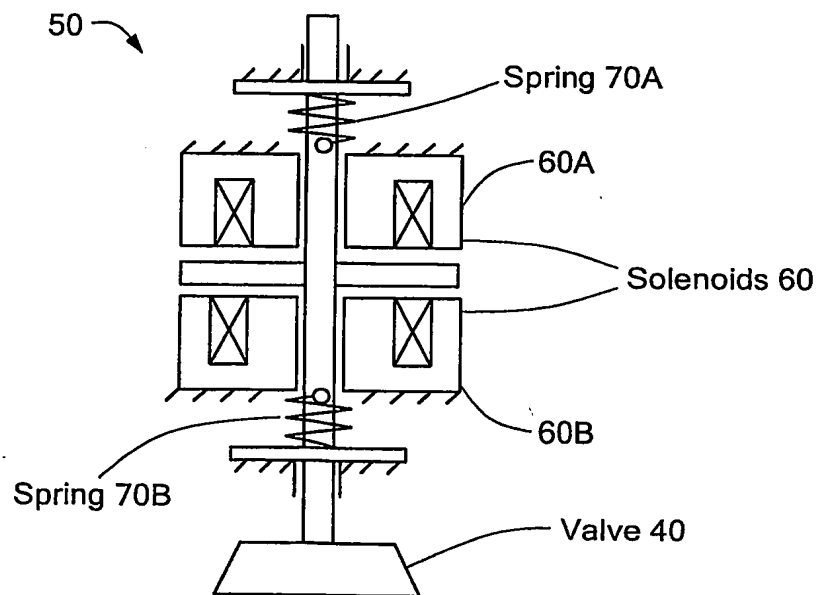
20 20. The valve drive assembly of claim 19 wherein said pivot element is movable in at least one direction selected from the group including a generally horizontal direction and a generally vertical direction.

1/18



Prior Art

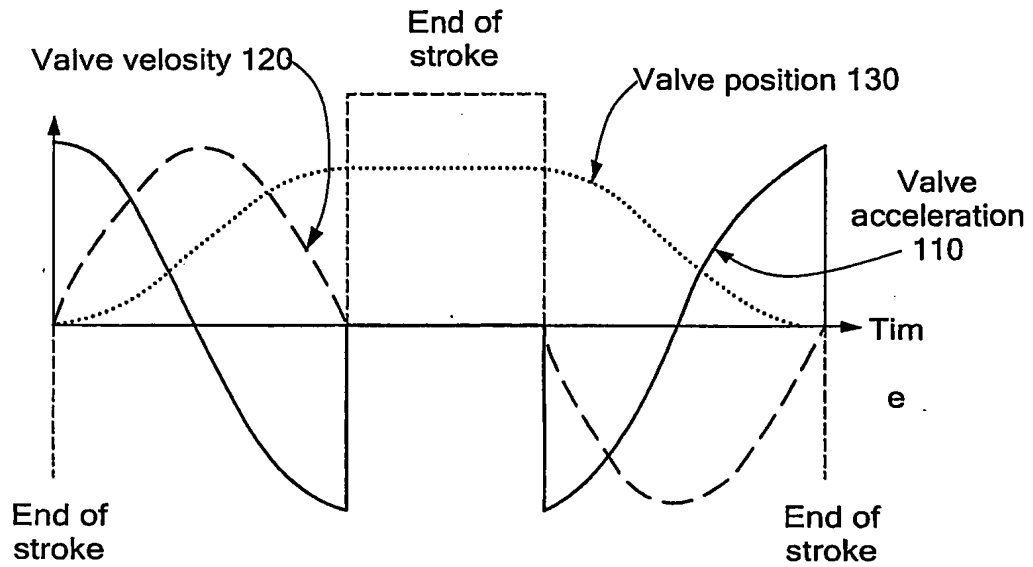
FIG. 1



Prior Art

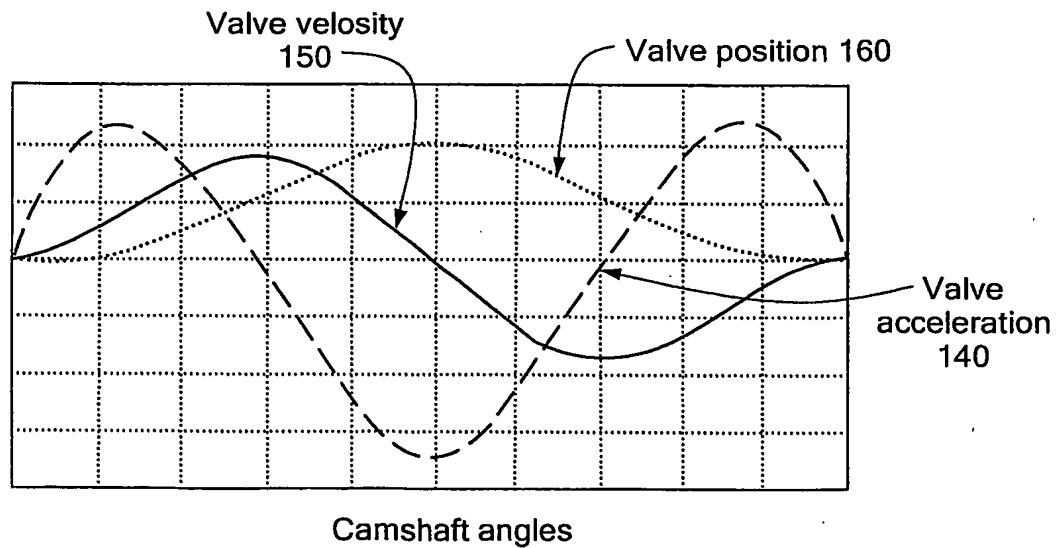
FIG. 2

2/18



Prior Art

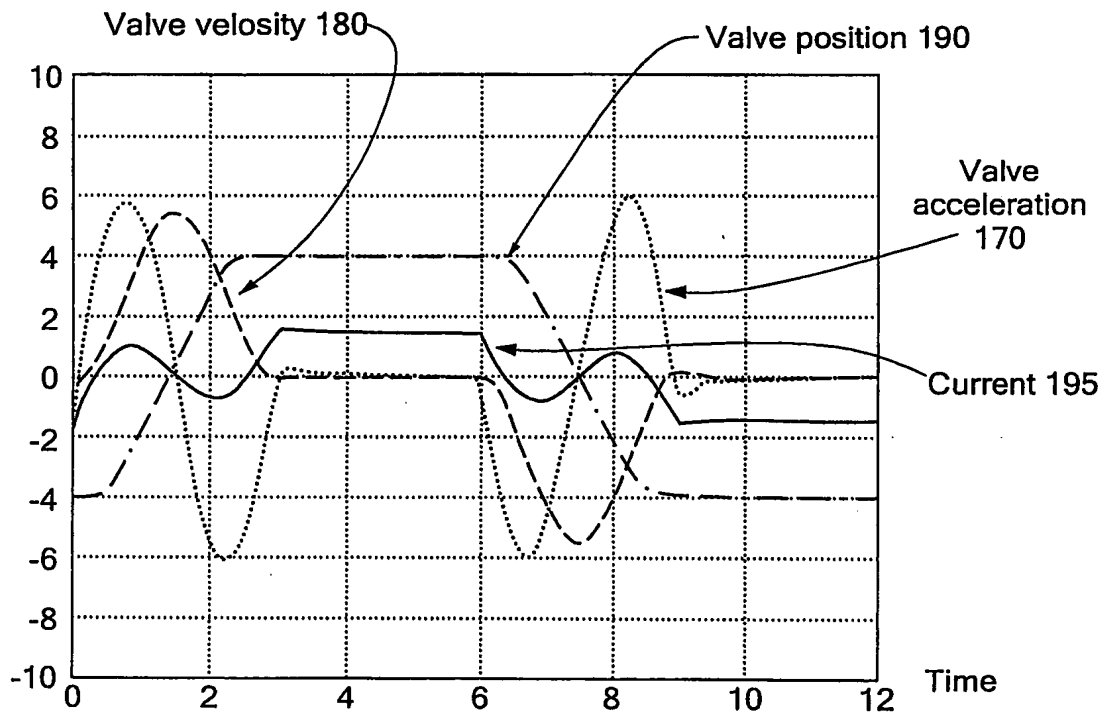
FIG. 3



Prior Art

FIG. 4

3/18



Prior Art

FIG. 5

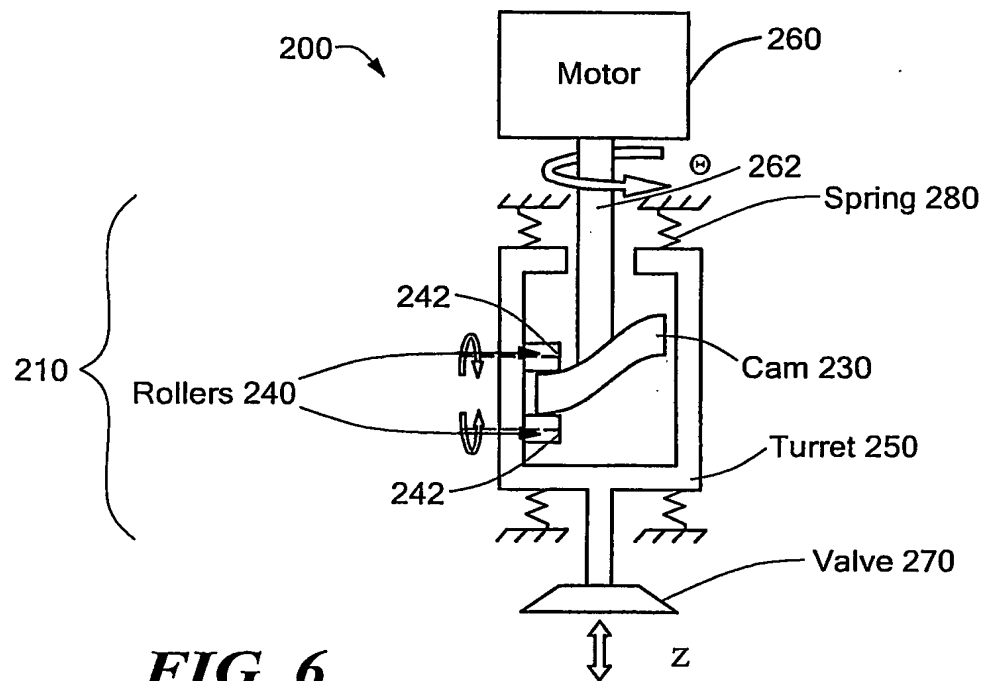
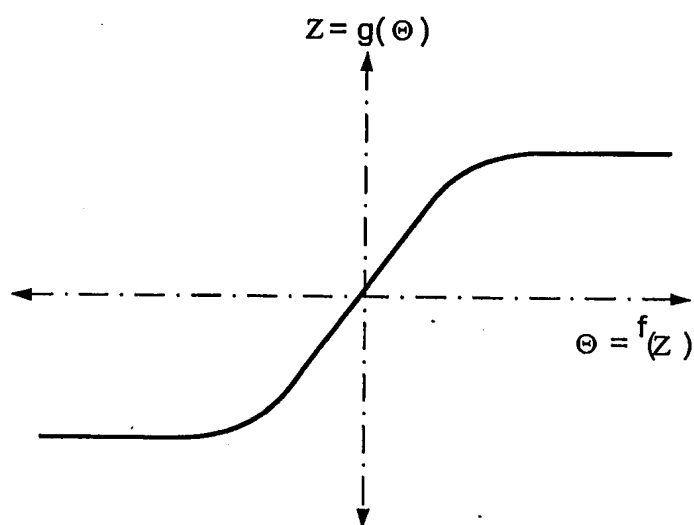
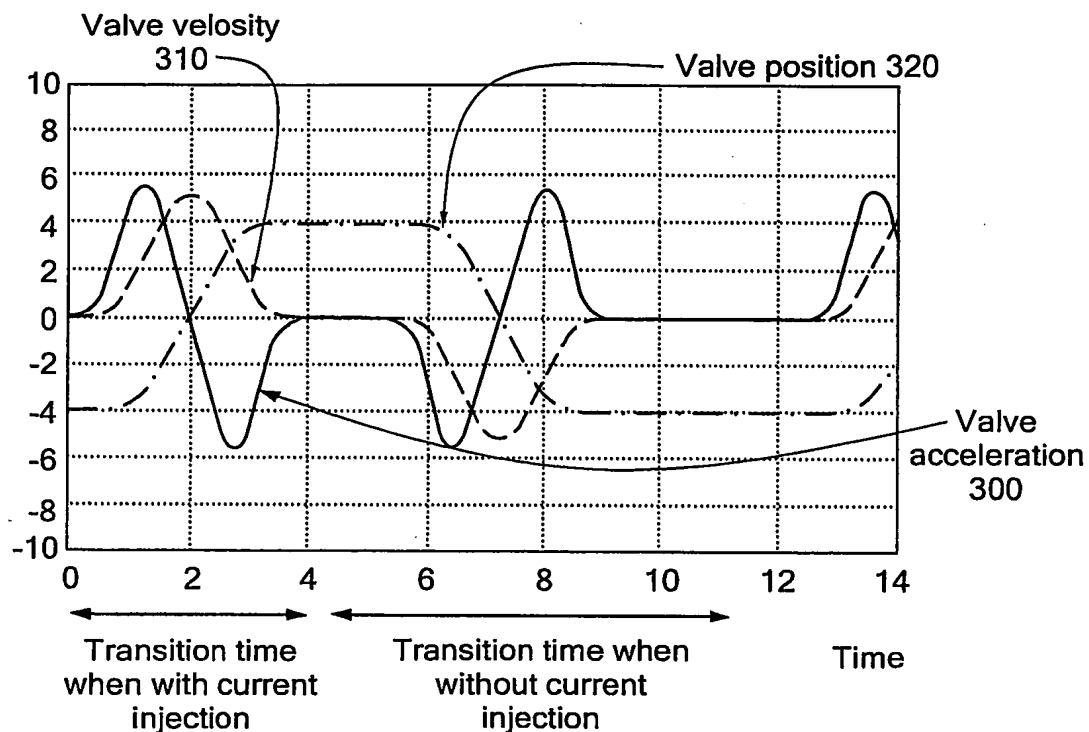


FIG. 6

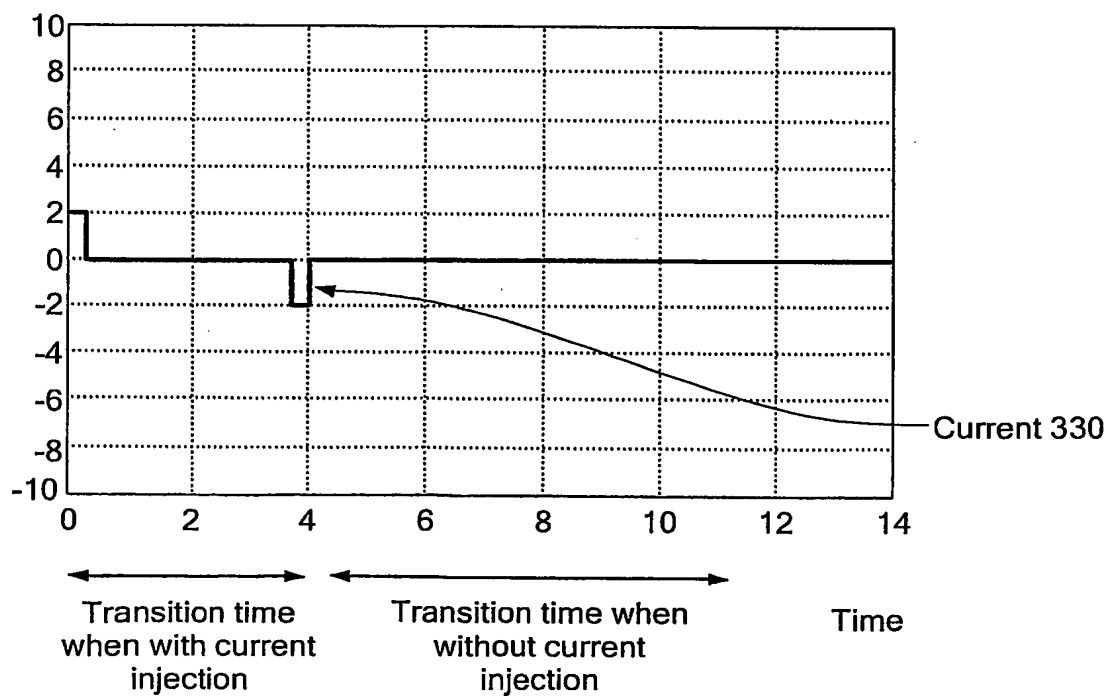
4/18

**FIG. 7**

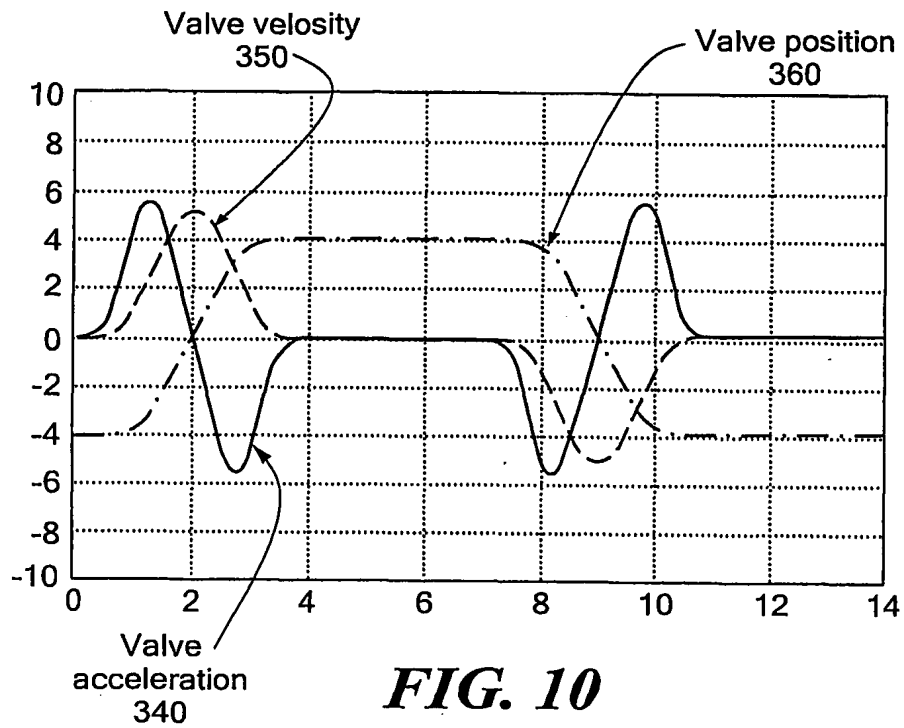
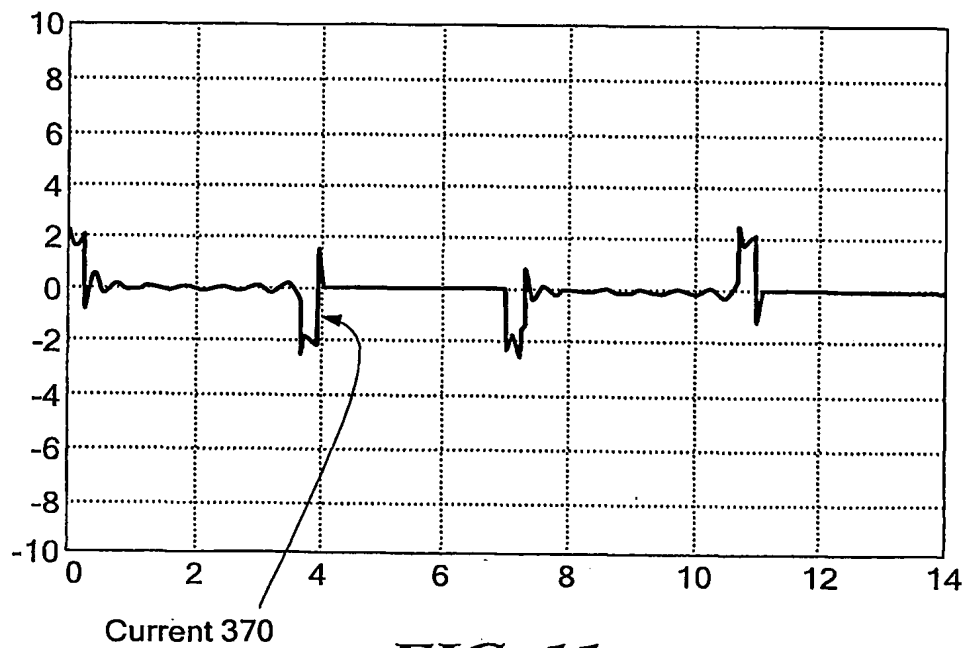
5/18



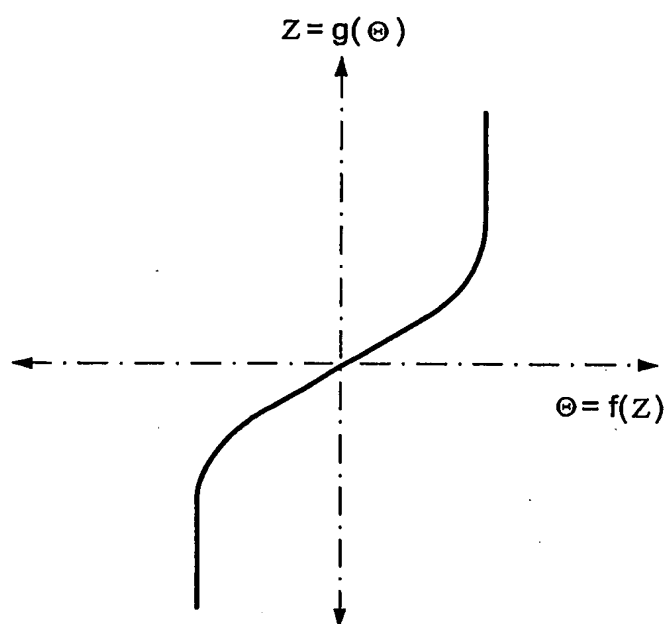
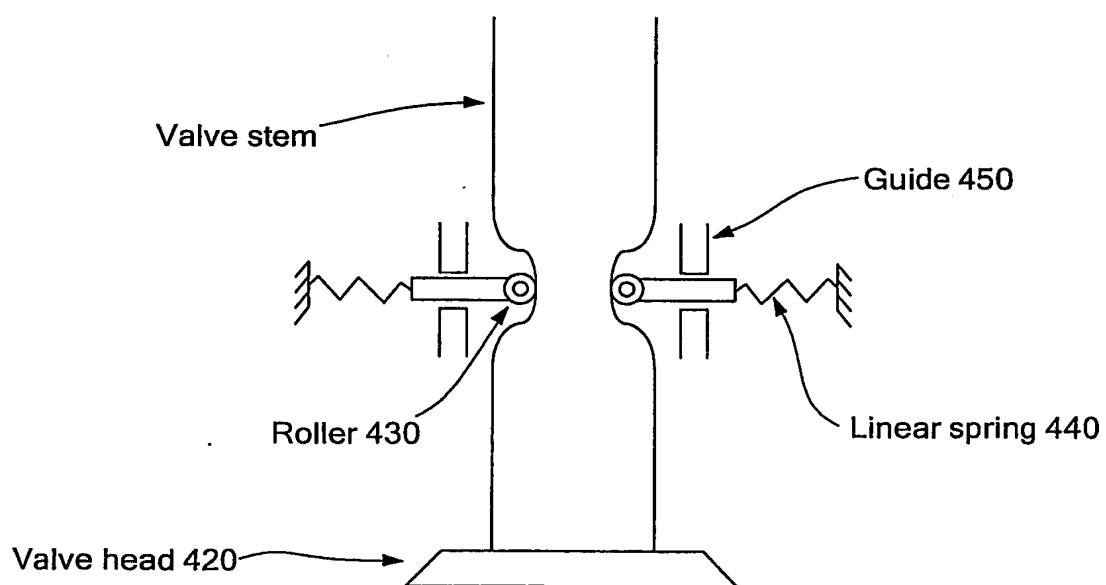
(a)

FIG. 8**FIG. 9**

6/18

**FIG. 10****FIG. 11**

7/18

**FIG. 12****FIG. 13**

8/18

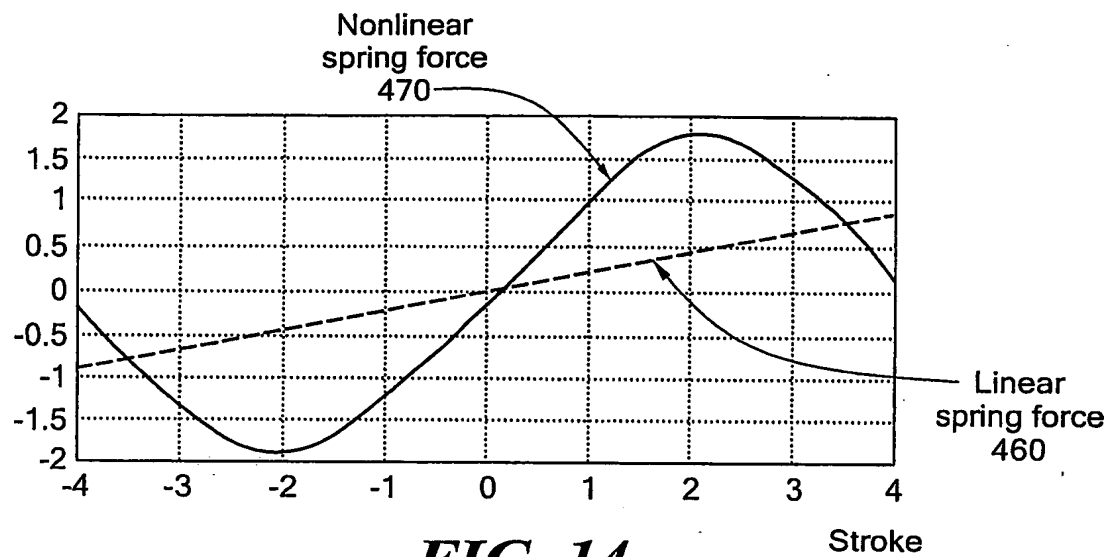


FIG. 14

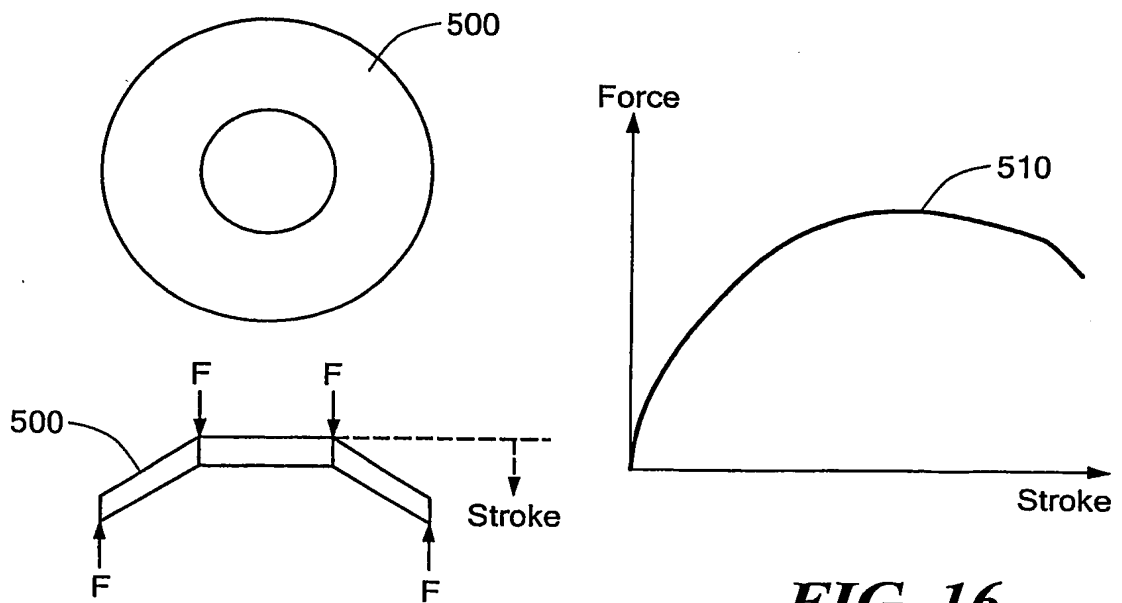
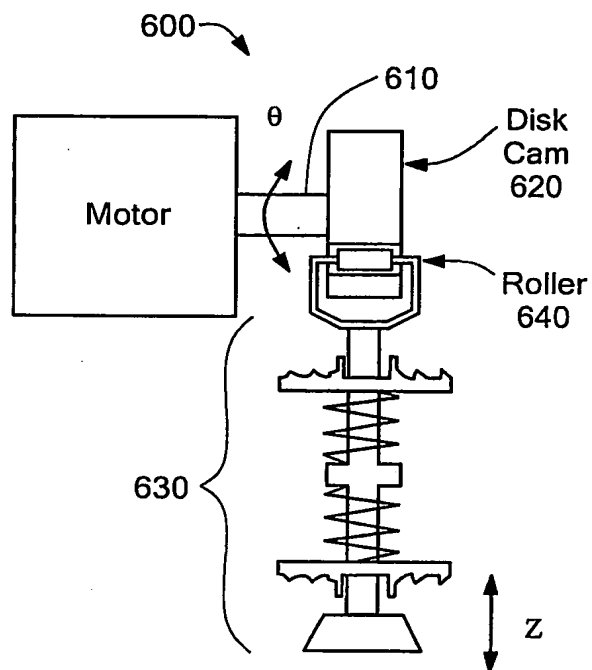
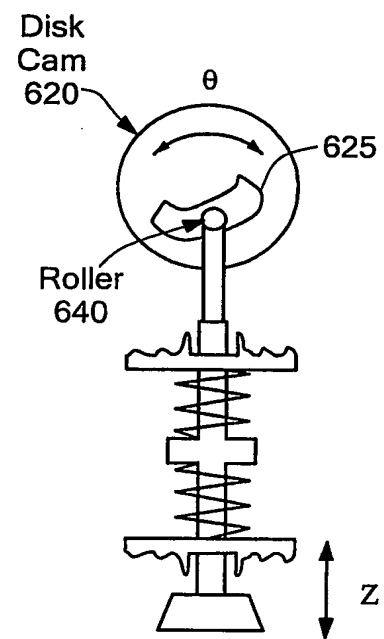
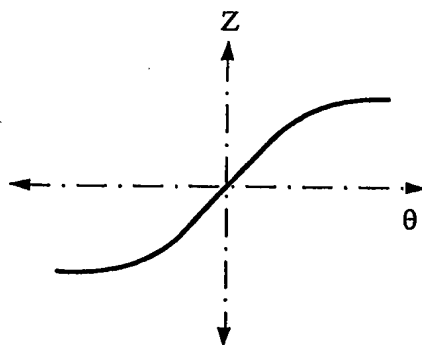


FIG. 16

FIG. 15

9/18

**FIG. 17a****FIG. 17b****FIG. 17c**

10/18

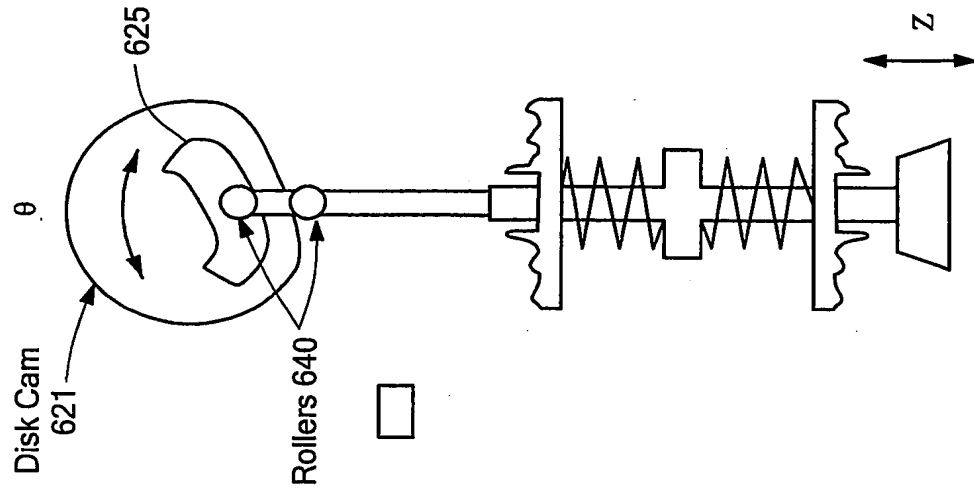


FIG. 18b

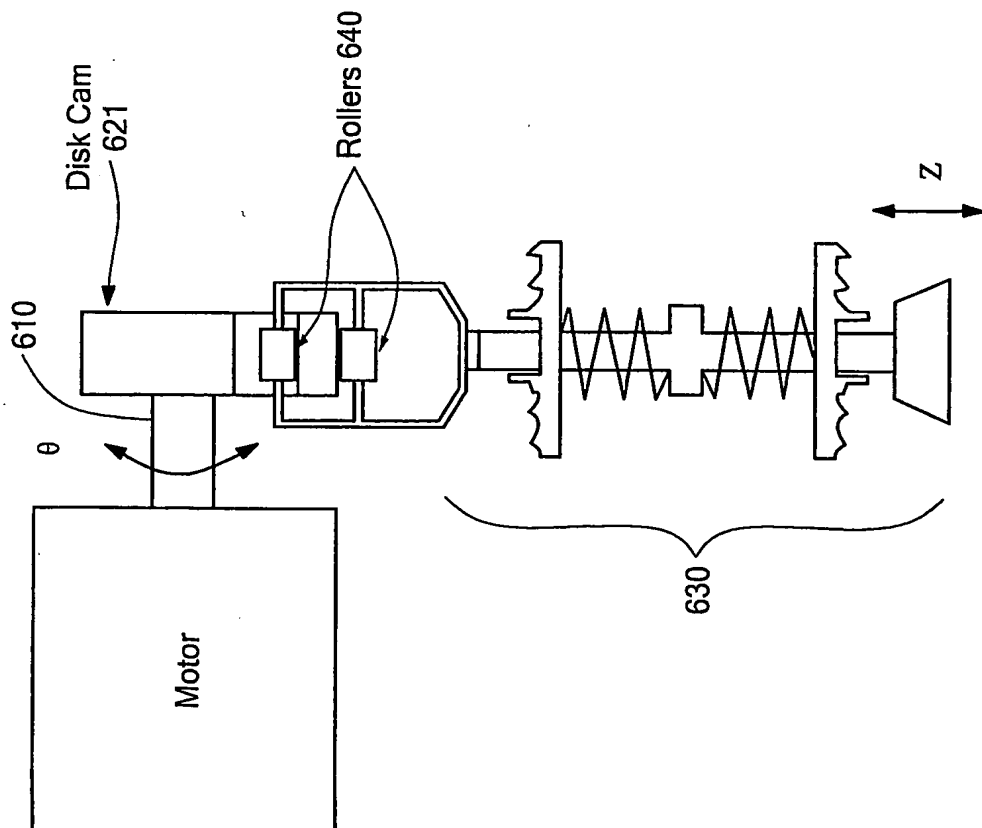


FIG. 18a

11/18

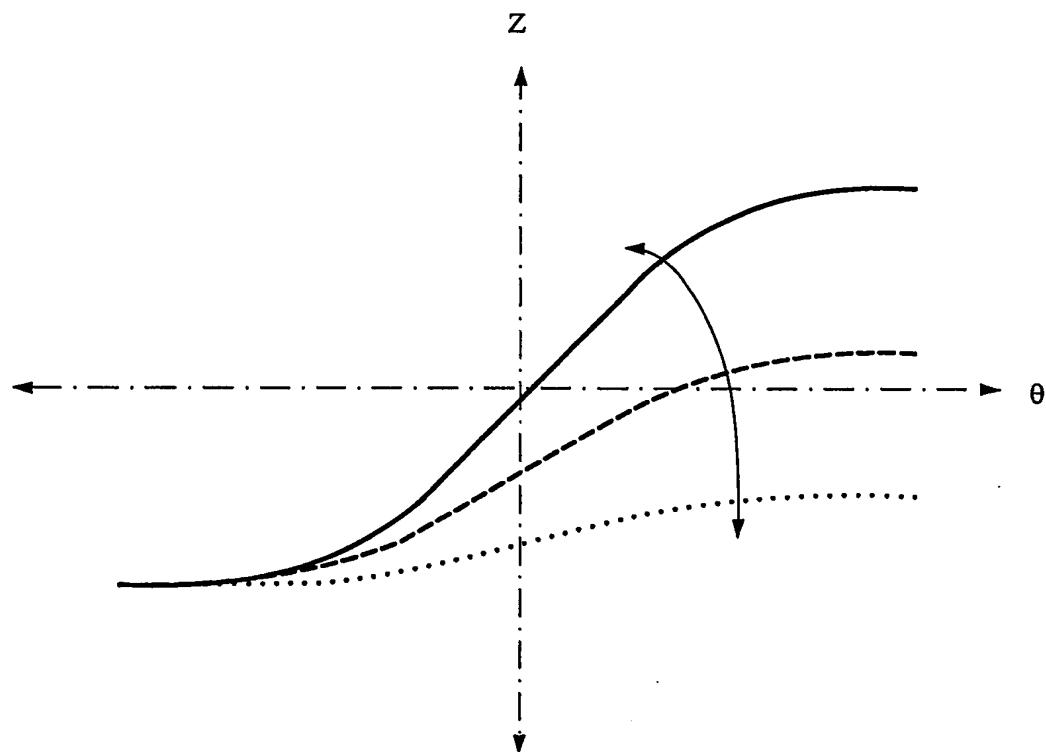


FIG. 19

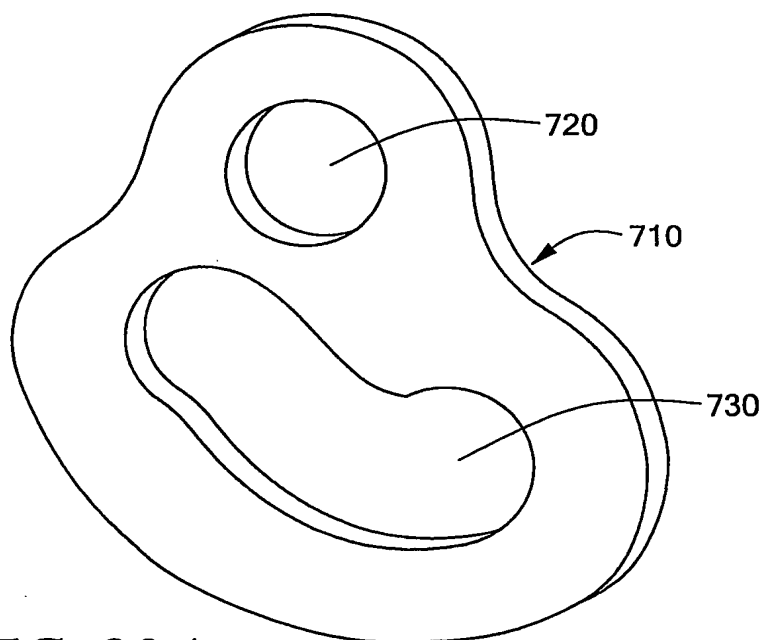
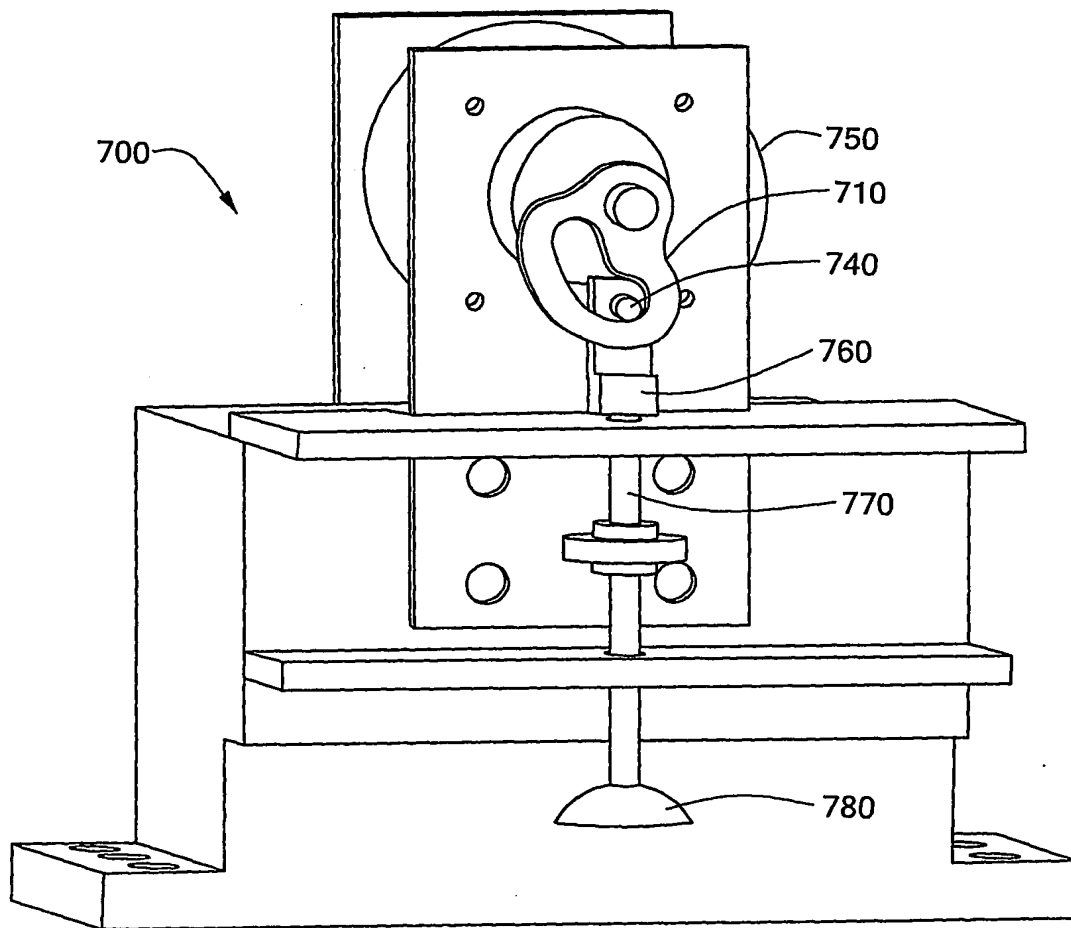
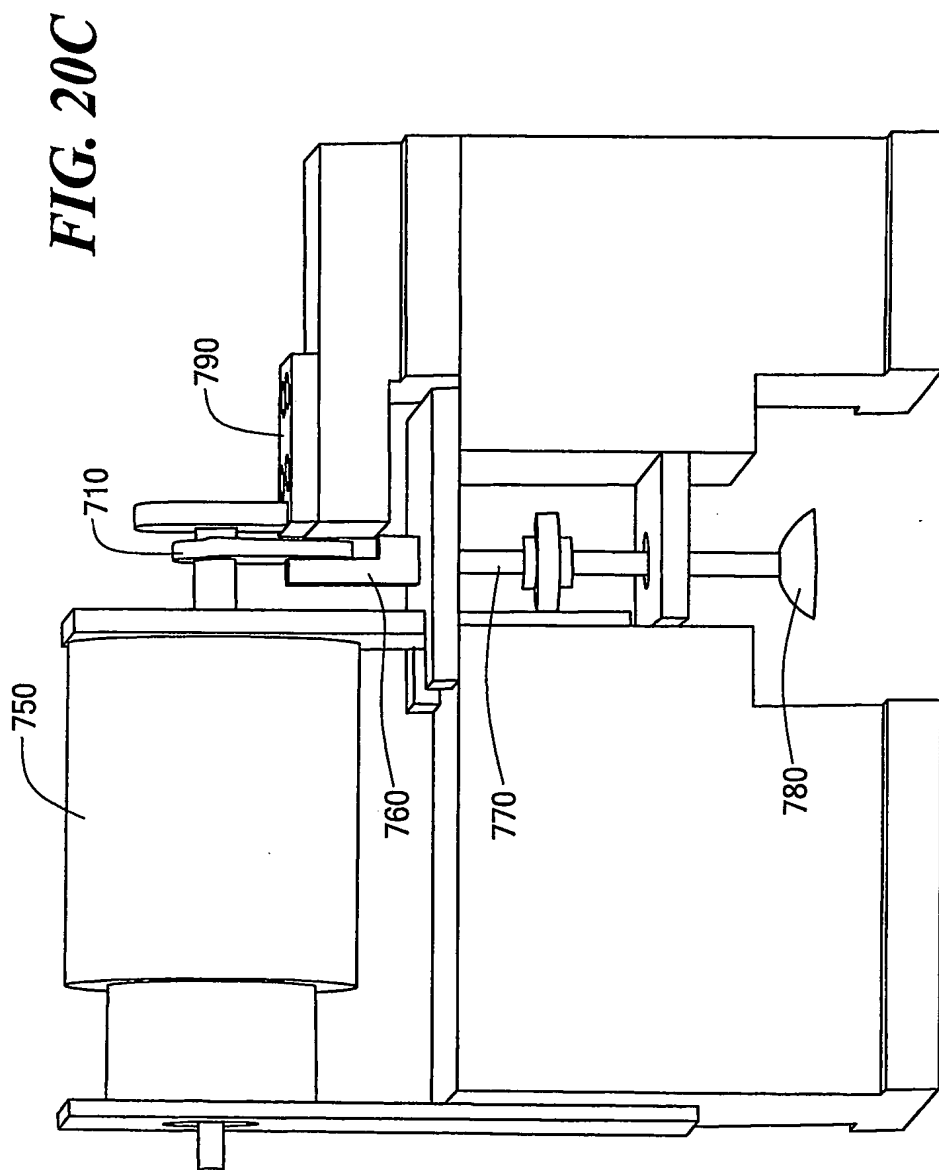


FIG. 20A

12/18

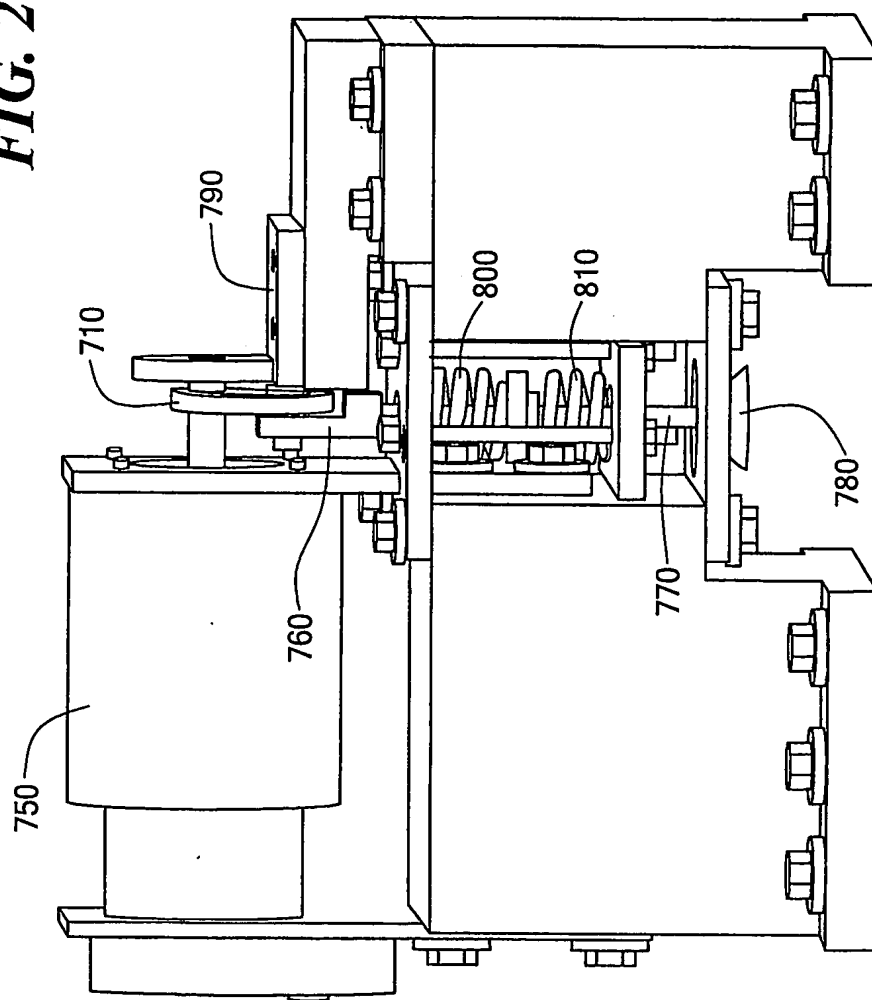
**FIG. 20B**

13/18



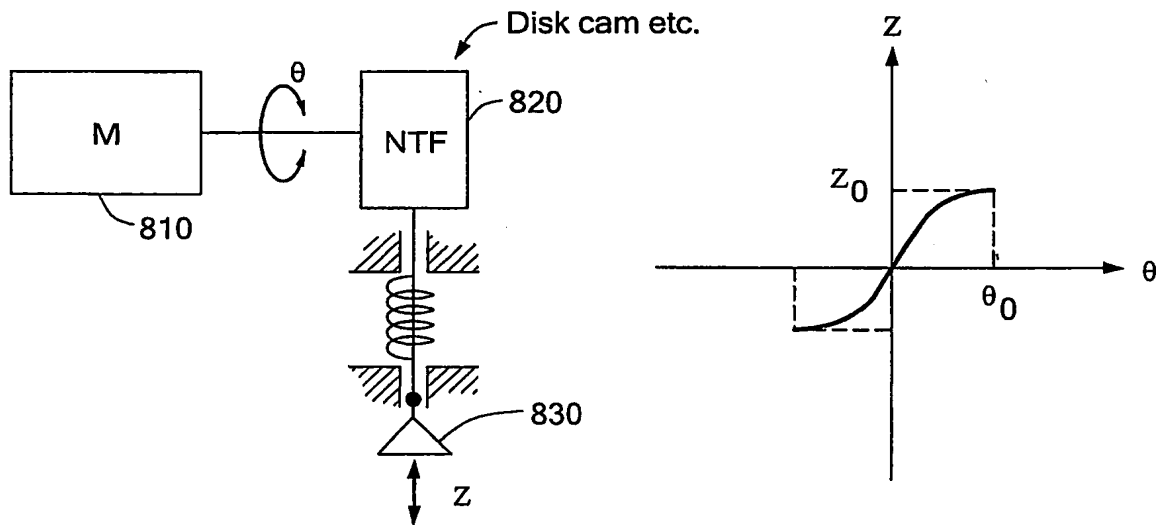
14/18

FIG. 20D

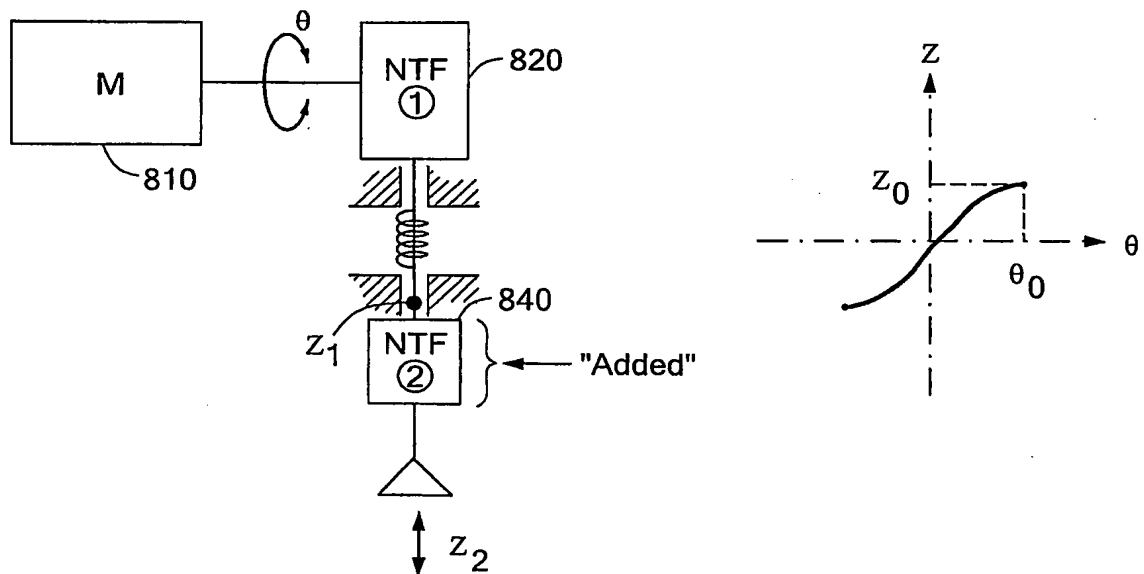


15/18

1. Before

**FIG. 21A**

2. After partial lift

**FIG. 21B**

16/18

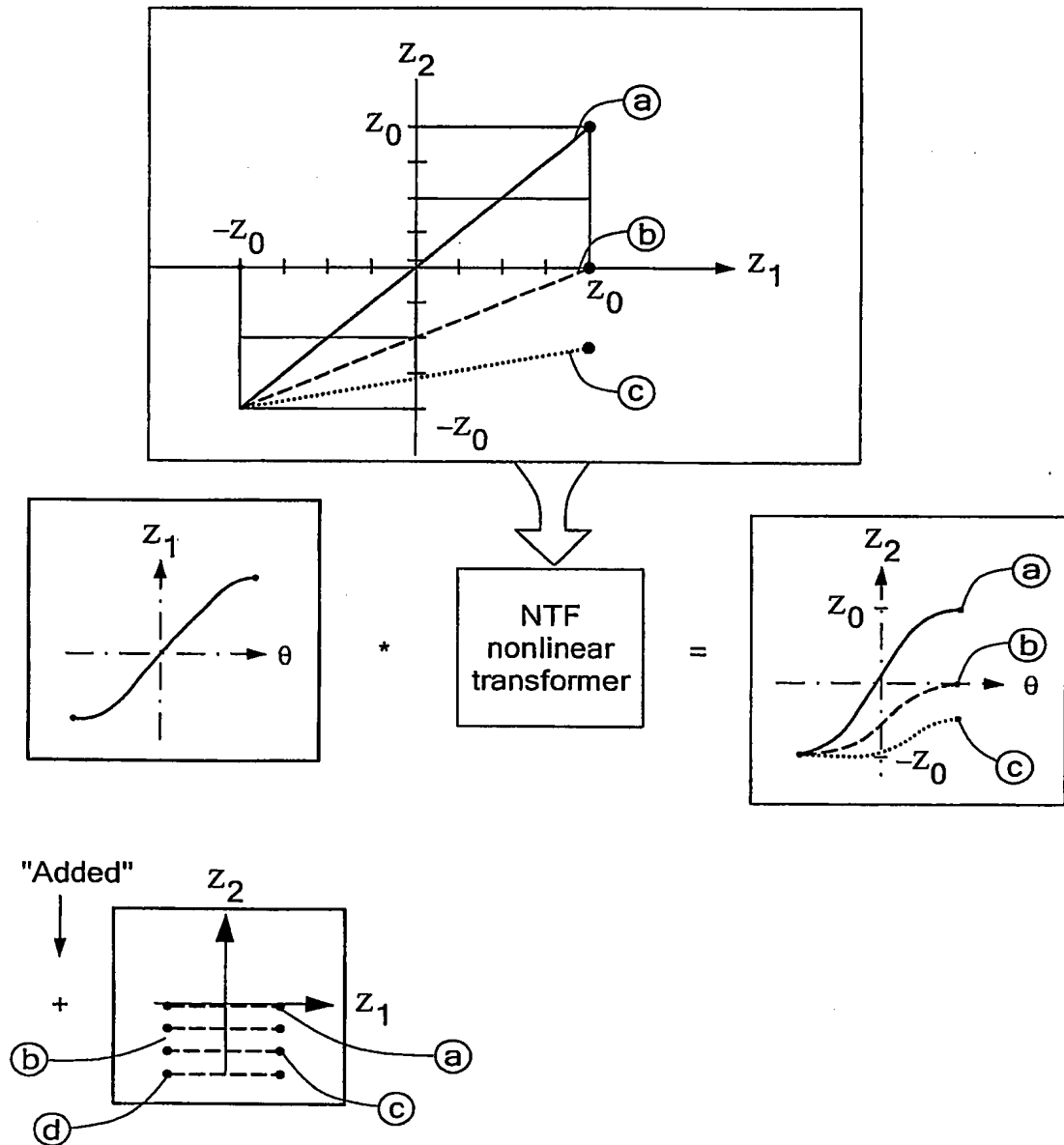
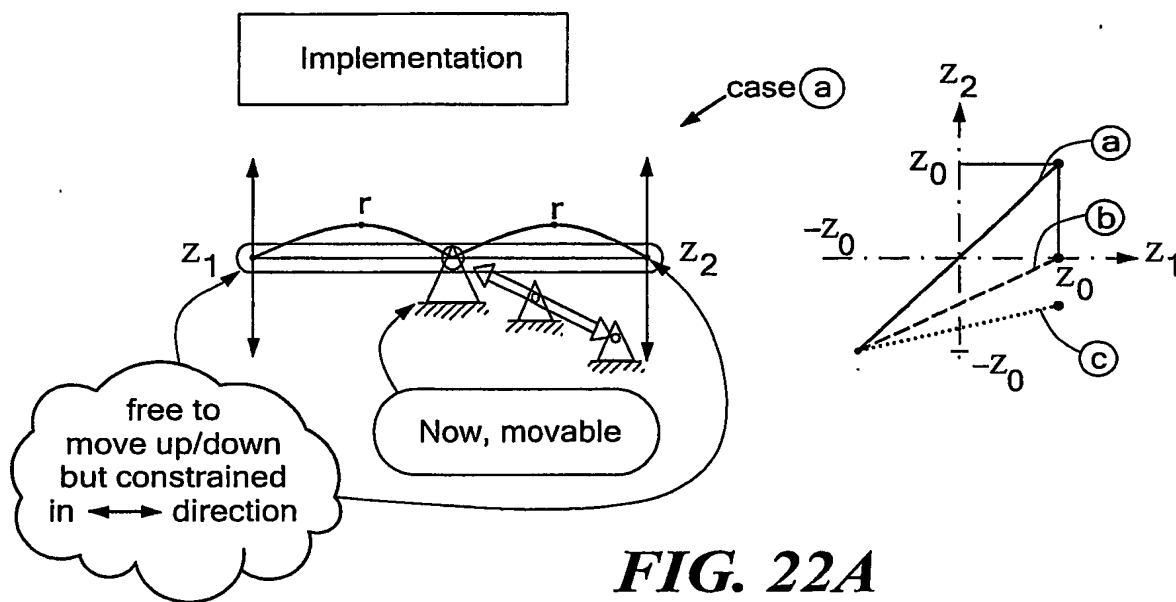
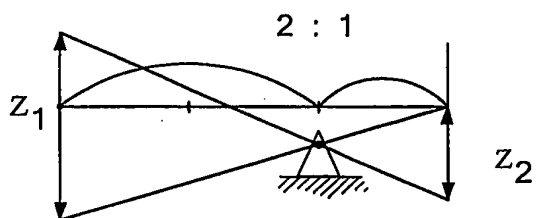


FIG. 21C

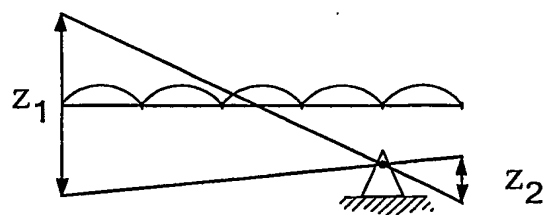
17/18



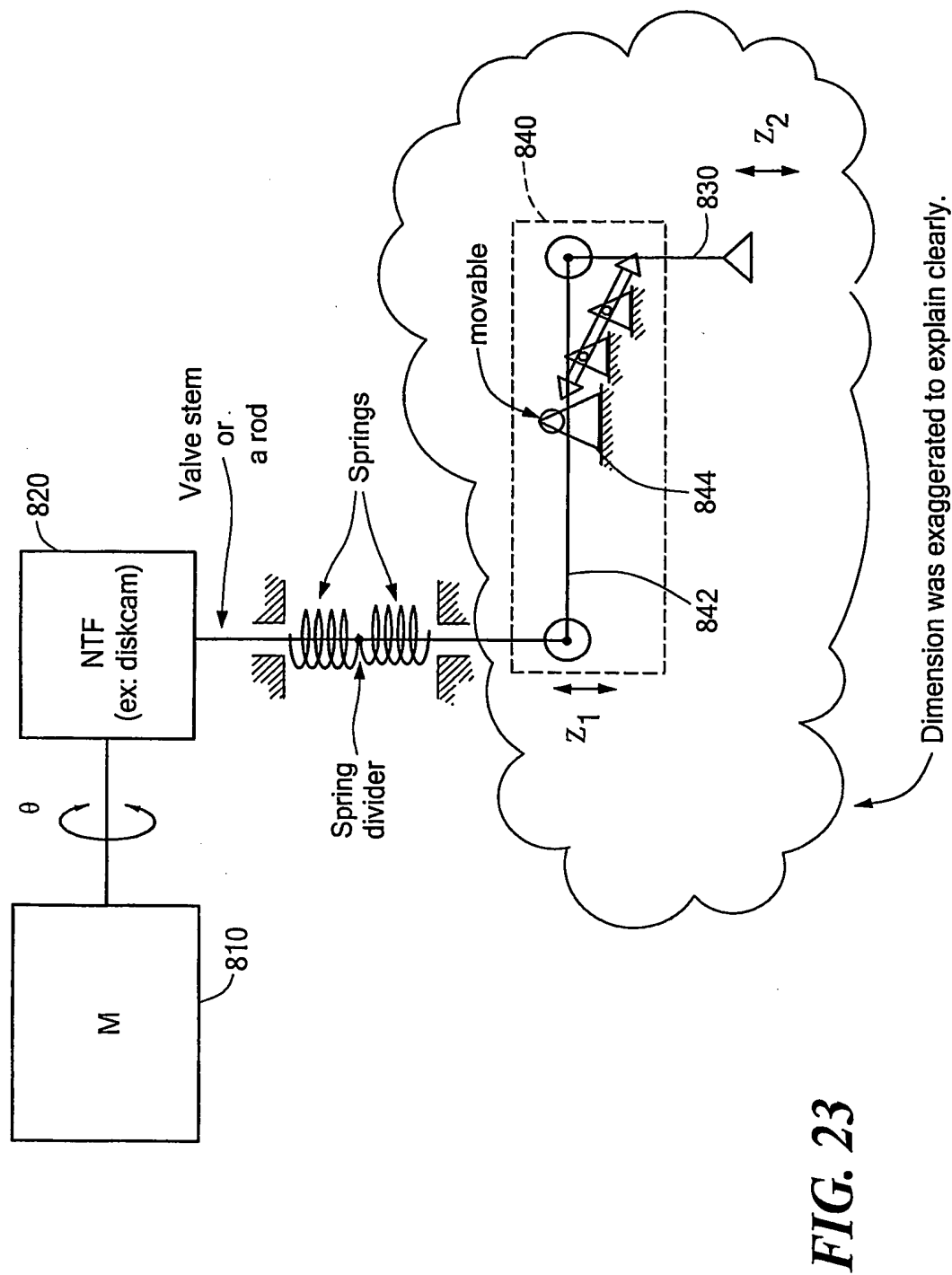
* For case (b)



* For case (c)



18/18



INTERNATIONAL SEARCH REPORT

International Application No

PCT/US 02/29359

A. CLASSIFICATION OF SUBJECT MATTER
 IPC 7 F01L1/30 F01L9/04

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC 7 F01L

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the International search (name of data base and, where practical, search terms used)

EPO-Internal, PAJ

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	JP 2001 152820-A (NISSAN MOTOR CO LTD) 5 June 2001 (2001-06-05) figures 1-12	1, 11-13
X	US 6 176 208 B1 (TSUZUKI YOSHIHIRO ET AL) 23 January 2001 (2001-01-23) column 7, line 56 -column 7, line 67	9
Y	column 7, line 26 -column 7, line 55	10
A	column 4, line 52 -column 4, line 55	1, 7, 11, 17-20
Y	US 5 211 372 A (SMITH JR JOSEPH L) 18 May 1993 (1993-05-18) claim 1; figure 2	10
	--- -/-	

☒ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

* Special categories of cited documents:

- *A* document defining the general state of the art which is not considered to be of particular relevance
- *E* earlier document but published on or after the International filing date
- *L* document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
- *O* document referring to an oral disclosure, use, exhibition or other means
- *P* document published prior to the International filing date but later than the priority date claimed

- *T* later document published after the International filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
- *X* document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
- *Y* document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.
- *G* document member of the same patent family

Date of the actual completion of the international search

5 November 2002

Date of mailing of the International search report

18/11/2002

Name and mailing address of the ISA

European Patent Office, P.B. 5818 Patentlaan 2
 NL - 2280 HV Rijswijk
 Tel. (+31-70) 340-2040, Tx. 31 651 epo nl,
 Fax (+31-70) 340-3016

Authorized officer

Clot, P

INTERNATIONAL SEARCH REPORT

In International Application No
PCT/US 02/29359

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT		
Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 5 598 814 A (HENRY RASSEM R ET AL) 4 February 1997 (1997-02-04) the whole document	1,2,4
A	US 5 245 957 A (BORNSTEIN IRVIN ET AL) 21 September 1993 (1993-09-21) claim 1; figures 1-3	1-4,6,11
A	US 5 873 335 A (WRIGHT DANNY O ET AL) 23 February 1999 (1999-02-23) column 3, line 49 -column 3, line 64; claim 1; figures 1,2,5 column 5, line 6 -column 5, line 23	11,12

INTERNATIONAL SEARCH REPORT

Int lional Application No

PCT/US 02/29359

Patent document cited in search report		Publication date	Patent family member(s)	Publication date
JP 2001152820	A	05-06-2001	NONE	
US 6176208	B1	23-01-2001	JP 11022432 A JP 11030114 A JP 11081940 A	26-01-1999 02-02-1999 26-03-1999
US 5211372	A	18-05-1993	JP 3249186 B2 JP 5187571 A	21-01-2002 27-07-1993
US 5598814	A	04-02-1997	US 5327856 A US 5494007 A DE 69302995 D1 DE 69302995 T2 EP 0603929 A1	12-07-1994 27-02-1996 11-07-1996 10-10-1996 29-06-1994
US 5245957	A	21-09-1993	AU 6028994 A WO 9418437 A1	29-08-1994 18-08-1994
US 5873335	A	23-02-1999	BR 9906814 A EP 1045960 A1 JP 2002500311 T WO 9935376 A1	10-10-2000 25-10-2000 08-01-2002 15-07-1999